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## Effects Of Fiber And Lithium On Mechanical Properties Of Concrete Made Fromrecycled Concrete Aggregate

Ashraf Eskander  
*University of Central Florida*



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EFFECTS OF FIBER AND LITHIUM ON MECHANICAL PROPERTIES OF  
CONCRETE MADE FROM  
RECYCLED CONCRETE AGGREGATE

by

ASHRAF ESKANDER  
B.S University of Assiut, 1992

A thesis submitted in partial fulfillment of the requirements  
for the degree of Master of Science  
in the Department of Civil and Environmental Engineering  
in the College of Engineering and Computer Science  
at the University of Central Florida  
Orlando, Florida

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## **ABSTRACT**

The growing demand of construction aggregates has raised concern about the availability of natural aggregates. Over two billion tons of natural aggregate are produced each year in the United States and that number is expected to increase to 2.5 billion tons by 2020. This has raised concern about the availability of natural aggregate. Discarding demolished concrete into landfills is a costly solution from an economical and environmental point of view. Many U.S. highway agencies are re-using Recycled Concrete Aggregates (RCA) as construction material. The use of fiber reinforcement in Portland Cement Concrete (PCC) has recently become a popular option in concrete construction because of its influence on preventing segregation, reducing early shrinkage cracks and increasing residual load capacity. Alkali-Silica Reaction (ASR) is a major problem in concrete, especially when using RCA, causing concrete expansion and cracks. Recently lithium has been found to reduce expansion due to ASR. This thesis will investigate the effect, of fibers soaked in lithium nitrate on the mechanical properties of RCA.

## **ACKNOWLEDGMENTS**

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## **CHAPTER 1**

### **INTRODUCTION**

The construction of highway bridges and buildings has been increasing for the past century, especially in the areas of dense population. These facilities need to be replaced or repaired because the end of service has been reached, and/or the original design no longer satisfies the needs of the population.

The growing demand of construction aggregates has raised concern about the availability of natural aggregates. Over two billion tons of natural aggregate are produced each year in the United States and that number is expected to increase to 2.5 billion tons by 2020. This has raised concern about the availability of natural aggregate. On the other side, the construction-demolished production has increased (estimated to be 123 million tons per year); this will open new sources of aggregates.

The most common method of managing these materials has been through disposal in landfills. Alternative uses of the waste material are becoming more important. This situation is leading state agencies and industries to begin recycling concrete as an alternative source of aggregates.

Portland Cement Concrete is considered to be a relatively brittle material. When subjected to tensile stresses, non-reinforced concrete will crack and fail. Recently,

specially engineered microfibers, such as acrylic, nylon, and polypropylene have been introduced into the concrete mixture to increase toughness resistance to cracking.

Fiber Reinforced Concrete (FRC) is Portland Cement Concrete reinforced with fibers.

In FRC, thousands of small fibers are distributed randomly in the concrete during mixing, therefore improving concrete properties in all directions. Fibers help to improve the post peak ductility performance, pre –crack tensile strength, fatigue strength, eliminate temperature, and shrinkage cracks.

Alkali-Silica Reaction (ASR) has a great impact on the service life of a concrete structure; it causes premature deterioration of concrete structures. ASR is one type of alkali-aggregation reactivity (AAR). ASR occurs between the alkalies produced from the hydration of Portland cement and certain siliceous rocks or minerals in the aggregates used in concrete production. Deterioration and expansion due to ASR is a two-step process. First, silica in the aggregate reacts with alkalies from the hydrated cement, forming a silica gel. Second, the gel absorbs water and begins to swell, causing expansive pressure sufficient to crack the concrete.

Research in the early 1950s found that lithium compounds were effective in preventing the expansion caused by alkali-silica reactions (McCoy and Caldwell 1951). The interest in using lithium in preventing ASR was renewed by studies performed in the Strategic Highway Research Program (SHRP) (Stark et al., 1993). Recent work on lithium compounds has been promising, so we will use the lithium admixtures to prevent damage resulting from ASR.

### **1.1. Objectives**

The objective of this thesis was to investigate the effect of fiber and lithium on the mechanical properties of concrete made with Recycled Concrete Aggregate (RCA).

### **1.2. Approach**

To achieve this objective, different concrete cylinders and beams were made with plain RCA, RCA with fiber, RCA with fiber soaked in lithium according to ASTM standards. These samples were tested to determine the compressive and flexure strength of the concrete.



## **CHAPTER 2**

### **LITERATURE REVIEW**

#### **2.1. Recycled Concrete Aggregates (RCA)**

RCA is generally comes from old Portland Cement Concrete (PCC) pavement, bridge structures, decks, sidewalks, curbs, and gutters that have been removed at the end of their service time. The debris cleaned of unwanted materials like bricks, wood, steel, ceramics, and glass. It is then crushed to a specific grade as RCA.

Federal Highway Administration (FHWA) has conducted a review on the uses of RCA in highway applications with the purpose of capturing the most advanced applications and technologies. This knowledge will then be transferred to the State Transportation Agencies (STAs) to review the best use of RCA, its advantages, and its barriers associated with highway construction.

To summarize the findings:

- STAs tend to reuse material recovered from either state projects or known sources of supply.
- Five states were identified as being among the highest consumers as well as large supply of RCA in the United States, including Texas, Virginia, Michigan, Minnesota, and California.
- 41 states recycle concrete as aggregate (Figure 2.1).
- 11 states use RCA in concrete (Figure 2.2).

- 38 states use RCA as a base and sub-base in pavements (Figure 2.3).

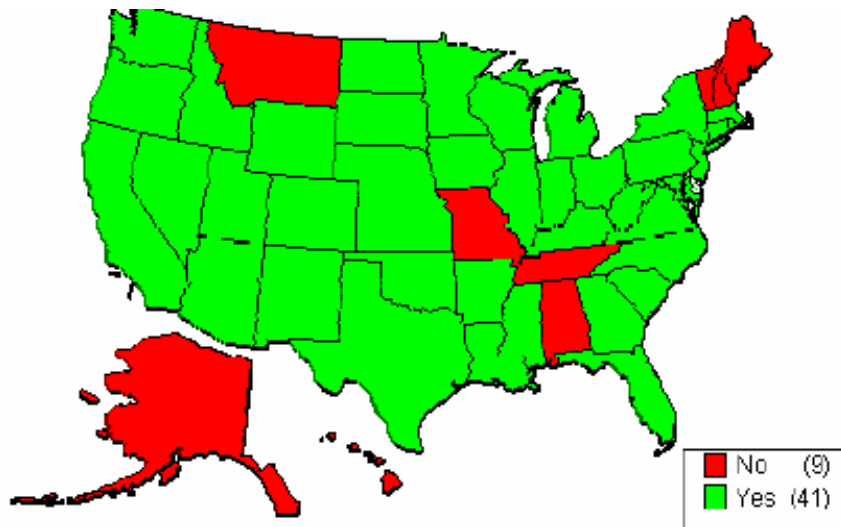


Figure 2-1: States recycling concrete as aggregate (FHWA, 2003)

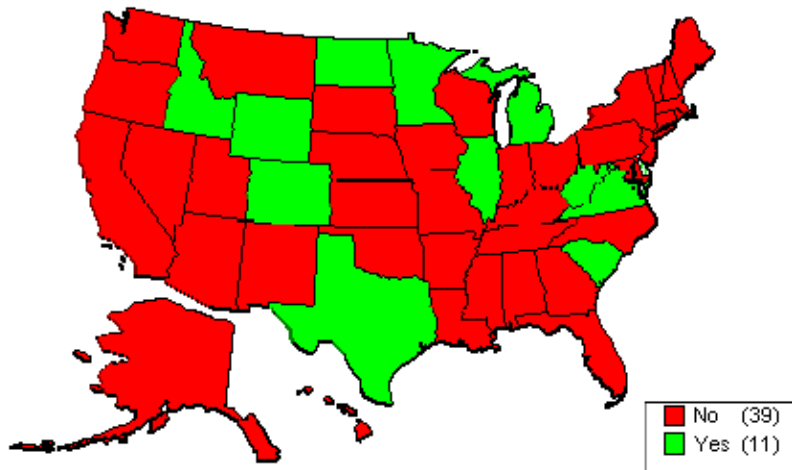
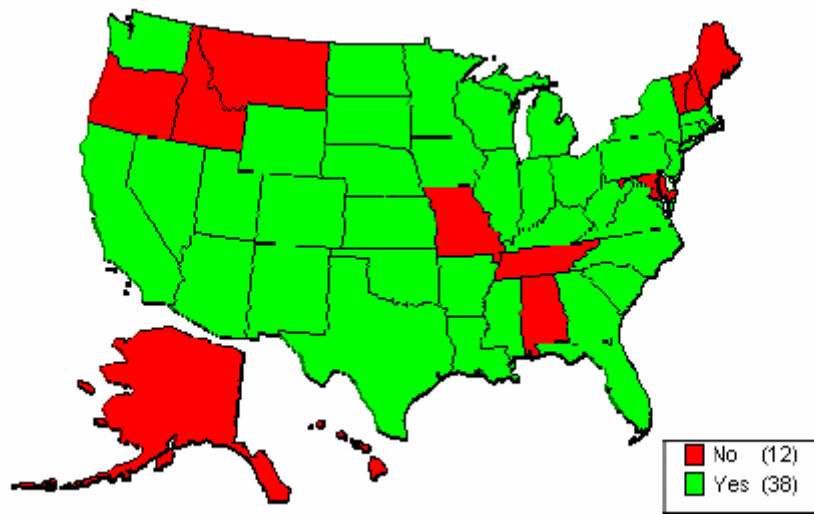


Figure 2-2: States recycling concrete as aggregate for PCC (FHWA, 2003)



*Figure 2-3: States recycling concrete as base and sub-base (FHWA, 2003)*

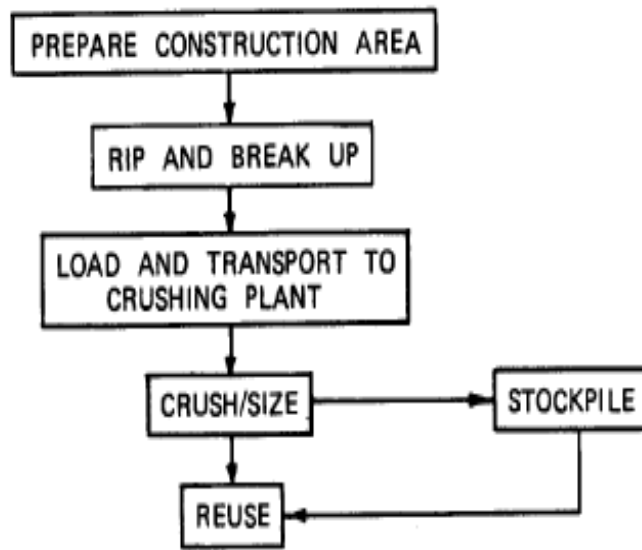
### **2.1.1. Validate RCA**

In order to consider the value of RCA, the reclaimed material must meet certain standards set by the Environmental Council of Concrete Organization (ECCO).

- RCA should be composed of (60 to 75%) of high quality well-graded aggregates bounded by hardened cement paste.
- RCA can have between 10% to 30% sub-base soil materials and asphalt from high way shoulder or composite type pavement.
- Lead toxic materials or any potentially harmful materials should not be presented on the RCA; these materials should be removed from the building before it is demolished.
- RCA should not contain any material that will react with the cement or reinforced concrete.

### **2.1.2. Recycling Portland Cement Concrete Procedure**

Portland Cement Concrete when removed as unwanted pavements and structural elements is usually wasted and disposed of outside of the project. However, the contractor may be given the option of recycling these materials as construction aggregates for Portland cement concrete pavement, cement-treated base (CTB), and/or aggregate base (AB). The basic process is shown in the flow chart Figure 2.4 (ECCO).



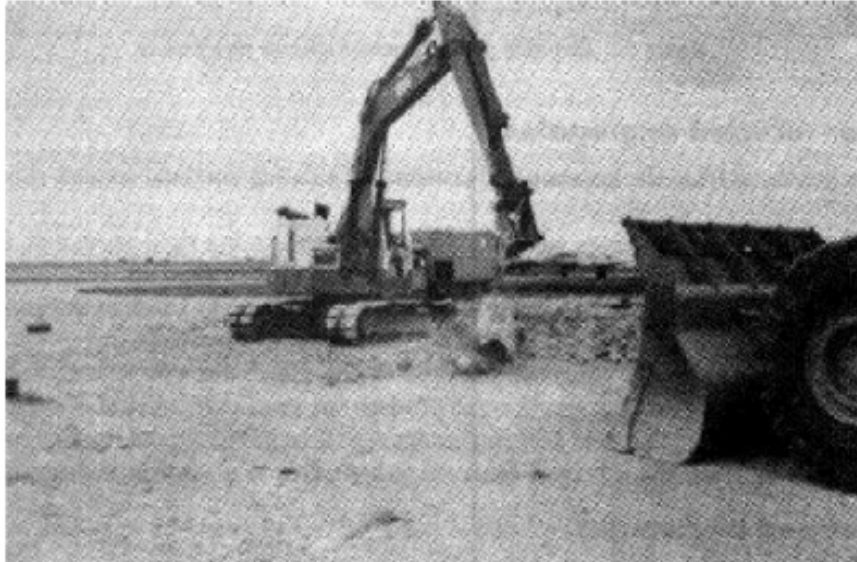
*Figure 2-4: Recycling Portland concrete flow process (ECCO)*

#### ***2.1.2.1.Break up***

The first step involves, preparing the existing pavement or other structural elements for fracturing into a manageable size. The pavement is broken by fracturing it with a pavement breaker, scarifying, ripping, or jack hammering as shown in Figures 2.5 and 2.6.



*Figure 2-5: Equipment used in breaking existing concrete (ECCO)*



*Figure 2-6: Equipment used in breaking and transfer concrete (ECCO)*

#### ***2.1.2.2.Load and Transfer***

After fracture, the broken concrete pieces are transferred to a crushing site. Cranes and front-end loader are used to load the rubble concrete into dump trucks or hauling to the crushing plant.

#### ***2.1.2.3.Crushing Process***

The crushing plants are either a portable type and located on the job site or a stationary plant situated at the existing pit or quarry. The equipment used to crush and size the existing concrete is also used in the construction industry. The crushing process consists of breaking the fractured concrete pieces to the required sizes and then stockpiling.

After salvaged concrete is brought to the crushing plant, it is reduced to the maximum specification size. The crushing equipment, which includes a jaw crusher, will break the material down to a maximum size of about 3". The secondary cone crusher breaks the particles down to the maximum size required depending upon specification and may vary between  $\frac{3}{4}$  and 2 inches (Figure 2.7).

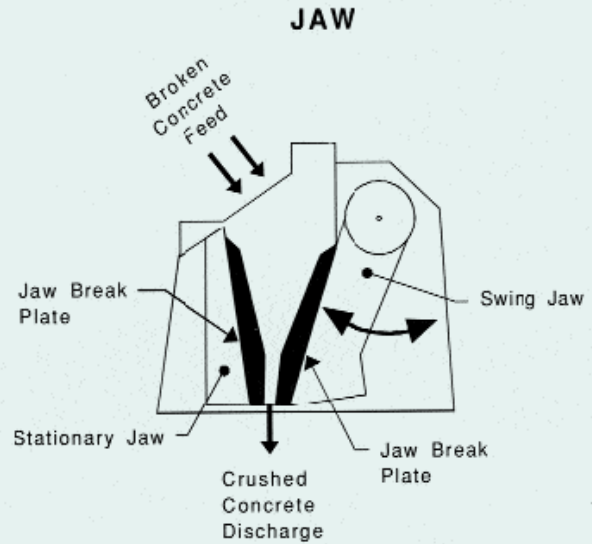
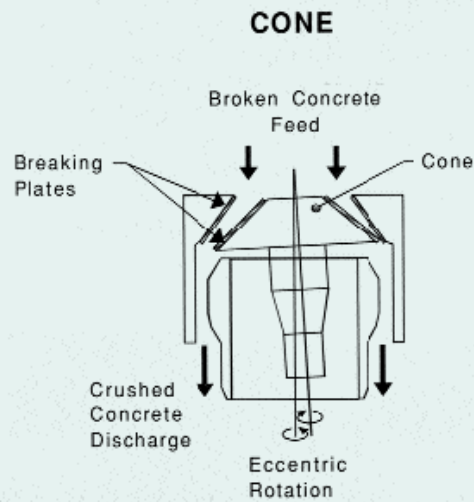
#### ***2.1.2.4. Stockpiling***

After crushing, the material is separated over screens and stockpiled separately. The stockpiling should be accomplished in a manner that will prevent contamination by foreign materials. Each size of aggregate should be stored separately in free-draining

stockpiles. Vehicles for stockpiling or moving aggregates should be kept clean from foreign materials.



## COMPRESSION CRUSHERS



## IMPACT CRUSHERS

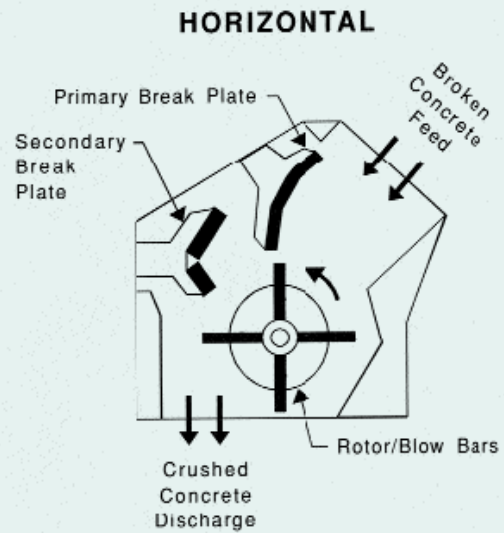
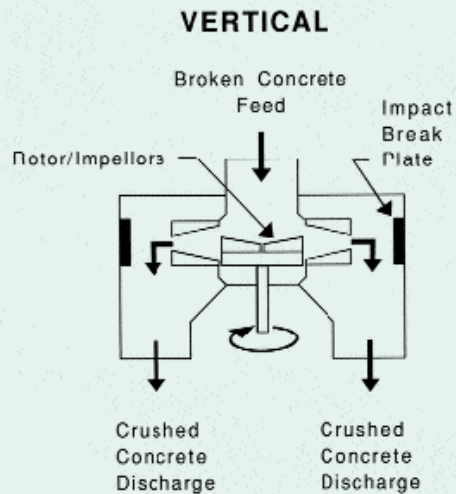


Figure 2-7: Three basic stone crushers. The impact crusher may be designed vertical or horizontal (ECCO)

### **2.1.3. Evaluation and Testing RCA**

These aggregates must meet the requirements for normal aggregates. The RCA will be subjected to all tests used to evaluate new aggregates as specified by ASTM.

#### ***2.1.3.1.D-Crack Concrete Pavement Recycling***

The deterioration of concrete pavement through D-cracking is a fairly widespread phenomenon. D-cracking occurs adjacent to joints and is caused by ASR and freeze/thaw problem. All recycled aggregates from an existing pavement that have experienced this type of deterioration must pass the  $\frac{3}{4}$  inch sieve if they are to be used as aggregates for a new Portland cement concrete pavement. Experience has shown that crushing the reclaimed Portland cement concrete to pass through the  $\frac{3}{4}$  inch sieve prevents d-cracks from reoccurring in the recycled pavement.

#### ***2.1.3.2.Fine Aggregates***

To improve workability of a new Portland cement concrete pavement using recycled concrete, natural sand can be added to the fine aggregates. however when two or more types of fine aggregate are used, each must be stockpiled separately.

#### ***2.1.3.3.Utilization of Recycled Aggregates***

Once the old PCC has been crushed and stockpiled, and the quality has been found to be satisfactory for its intended use, the material will then be treated as an aggregate.

Applicable documents need to be prepared as a guide.

#### **2.1.4. Properties of RCA**

Many tests have been done to determine the properties of recycled aggregates derived from waste concrete. The majority of these tests try to determine the properties of these aggregates to fulfill uses in construction. The properties of RCA are different from the virgin aggregate in much aspect, such as, different particle size, different shape, density, and the mortar attached to the surface of the aggregates.

##### ***2.1.4.1.Mechanical Properties***

The mechanical properties of concrete made with virgin aggregates have a greater compressive strength than concrete made by RCA. Other significant properties such as tensile strength and flexure strength are lower for RCA. Creep and shrinkage are also higher in the concrete made with RCA. The difference in strength depends on the fraction of total recycled aggregates, the characteristic of the original concrete, the nature and level of contaminant present, the amounts of fines, and the quantity of the attached mortar.

#### ***2.1.4.2. Physical Properties***

Processed RCA, which is 100 percent crushed material, is highly angular in shape. Due to the adhesion of mortar to the aggregates incorporated in the concrete, processed RCA has rougher surface texture, lower specific gravity, and higher water absorption than comparatively sized virgin aggregates.

During processing, RCA particle size decreases, there is a corresponding decrease in specific gravity and increase in absorption, due to the higher mortar proportion adhering to finer aggregates. High absorption is particularly noticeable in crushed fine material, which is less than 4.75 mm in size (No. 4 sieve size) and particularly in material from air-entrained concrete (since there is substantially more air-entrained mortar in the fine than the coarse RCA aggregates). The 0.075 mm (No. 200 sieve) fraction is usually minimal in the RCA product. Some typical physical properties of processed RCA are listed in Table 2.1.

*Table 2-1: RCA physical properties (FHWA)*

Property	Value
Specific Gravity	
- Coarse particles	2.2 to 2.5
- Fine particles	2.0 to 2.3
Absorption, %	
- Coarse particles	2 to 6
- Fine particles	4 to 8 <sup>(a)</sup>
a. Absorption values as high as 11.8 percent have been reported.	

#### ***2.1.4.3. Chemical Properties***

The cement paste component of RCA has a substantial influence on RCA alkalinity. Cement paste consists of a series of calcium-aluminum-silicate compounds, including calcium hydroxide, which is highly alkaline. The pH of RCA-water mixtures often exceeds 11. RCA may be contaminated with chloride ions from the application of deicing salts on roadway surfaces or with sulfates from contact with sulfate-rich soils. Chloride ions are associated with corrosion of steel, while sulfate reactions lead to expansive disintegration of cement paste. RCA may also contain aggregate susceptible ASR. When incorporated in concrete, ASR-susceptible aggregates may cause expansion and cracking. The high alkalinity of RCA, in the presence of moisture, can result in corrosion of aluminum or galvanized steel pipes in direct contact with RCA.

### **2.1.5. Construction of RCA**

Several issues appear when using recycled aggregate in lieu of virgin aggregates. The recycled aggregates have a higher absorption and lower specific gravity than the original aggregate. This is due to the inclusion of the mortar made up of the cement, water, and air. These characteristics need to be considered in the design of the concrete mixture.

#### ***2.1.5.1. Water Demand***

When RCA is used in new concrete, achieving and maintaining plastic properties similar to concrete made with virgin aggregate requires special attention. In general, the RCA must be handled as a lightweight aggregate, which has higher water absorption. It is important to maintain the aggregate in a saturated surface dry (SSD) condition to assure the PCC mix water, as designed, is maintained as to produce uniform plastic properties at constant water to cement ratio. Lightweight aggregate piles should be constantly sprayed with a garden sprinkler to assure saturation prior to batching. Development and control of an adequate procedure is required to assure that constant plastic properties of the RCA concrete, equivalent to that of concrete made with virgin aggregate. Maintaining a consistent and uniform SSD condition is also key to achieving a workable mix. Concrete made using RCA should needs approximately 5% more water than similar PCC with natural course stone (additional water is needed if percent of fines increase, up to about 15% more water). In the event that freeze-thaw durability is a concern, a lower amount of fines should be used.

#### ***2.1.5.2. Workability***

Workability of a properly designed RCA mix is similar to the conventional concrete mix. Conventional equipment and procedures commonly used to mix, place, and finish conventional concrete work equally well for RCA concrete. Some agencies initially experienced workability issues. As a result, these agencies limit the amount of RCA fines to 20% in the mix. This has been documented in the American Concrete Institute and work in Michigan during the early 1990 s.

#### ***2.1.5.3. Air Entraining***

Concrete must be evaluated for use as RCA in new concrete as any new aggregate. One important property of the original concrete feedstock is that it contains sample-entrained air. Although possible, it is not economical, to attempt to make quality concrete out of inferior feedstock. The new mix must contain entrained air like any other concrete. Conventional criteria for specifying the air void system are appropriate for RCA concrete. Dosages required to achieve a given level of air entraining tends to be slightly less than required for conventional aggregates. This is due to increased angularity and possibly increased fines in the mixing process. It should be noted if the RCA had poor resistance to freezing, the PCC made from that would also experience poor durability.

#### ***2.1.5.4. Compaction and Drainage Requirements***

When RCA is used as base material, special handling procedures are required to assure proper transportation, placement, and compaction are achieved. It is necessary to wet the material in order to prevent dust particles from becoming airborne just like any other aggregate base material. Proctor testing, typically required for conventional base materials, and is not required when RCA is specified for a base. Excessive working of the RCA base should be avoided; it will segregate the base materials. Minimum shaping of the RCA base material should occur. Compaction of the RCA base should be in a saturated state to aid in the migration of fines throughout the mix. Moisture levels are maintained and compaction is continued until the maximum level of compaction is achieved for the equipment being used. This procedure has been found to be very effective in obtaining very dense bases. TxDOT recommended that compaction should be performed with steel wheel rollers, because of minor amounts of steel present in the RCA base that could cause problems when using rubber tired equipment. Quality crushing operations should eliminate this concern.

#### **2.1.6. Summary of States Experiences**

Transportation agencies experimented and researched studies have shown recycled concrete aggregates, under specific conditions, have a potential to produce strong durable aggregates suitable for use in highway construction.



#### ***2.1.6.1. Summary of Texas Department of Transportation TxDOT***

- The use of RCA in new concrete initially created problems with mix workability. The problem associated with the high absorbency of water and the difficulty in maintaining a consistent and uniform saturated surface dry condition of RCA aggregate. Research has identified an increase in creep and shrinkage when RCA is incorporated into new concrete, for that reason, RCA is not used in concrete.
- TxDOT initially experienced lower compressive strength and workability issues. Research linked the use of RCA fines in the concrete to the lower compressive strengths and workability. At that time it was determined that 20% was the maximum amount of RCA fines that would be allowed in the concrete.
- The placement of RCA base material has provided some hurdles in grading and compacting. Excessive working of the RCA base will segregate the base materials. Minimum shaping of the RCA base material should occur. Compaction of the RCA base should be in a saturated state to aid in the migration of fines throughout the mix. Overall the performance of RCA as a base material has been excellent, a material even tend to knit together and has a higher load bearing capacity due to the re-cementing action.

#### ***2.1.6.2. Summary of Virginia Department of Transportation VDOT***

- When use RCA in base and sub-base, RCA should be compact in a saturated condition to aid in the migration of fines throughout the mix. Compaction of the RCA should be performed with steel wheel rollers, because of minor amounts of steel are present in the material and may cause problems when using rubber-tired equipment.

### ***2.1.6.3. Summary of Minnesota Department of Transportation Mn/DOT***

- Mn/DOT developed a standard specification for using RCA in construction construct. These specifications establish that RCA can be used as coarse aggregate in Portland cement concrete (PCC) in section 3137.2 B, as aggregate for surface and base courses in section 3138.2 A, and as granular material in section 3149.2.
- Minnesota currently uses almost 100% of the concrete removed from its pavements as dense graded aggregate base. This material must meet the 3138.2 section of Mn/DOT specification and can include a maximum of 3% by mass of asphalt binder from recycled asphalt pavement.
- From the late 1970 s through the 1990 s, RCA was used as coarse aggregate for PCC pavements on more than 20 projects. Today, Mn/DOT uses a 60-year pavement design life on its high-volume freeways and a 35-year design life on all other highways with associated warranties. These factors have limit-using RCA in new concrete.
- Observations suggest that RCA, when used in the base and sub-base material, performs better than virgin aggregate. Research is underway to determine if the observed increase in base strength can be validated in a laboratory performance evaluation for RCA used in aggregate base and sub-base.

- Substitution of RCA for virgin aggregate can provide savings in the final cost of the project. It is a common practice in Minnesota to crush the material on site. This lowers the transportation costs and has less effect on traffic.
- Washing of RCA is required if used in PCC pavements in order to eliminate excess fines. Quality requirements for new aggregate do not specifically apply to RCA when the pavement comes from a known source.
- In presence of drainage layers and/or perforated drainage pipes a blend of RCA with new aggregate may be used as sub-grade when at least 95% of the RCA is retained on the 4.75 mm sieve.

#### ***2.1.6.4. Summary of California Department of Transportation (CALTRANS)***

Most of the concrete pavement removed from existing highways and streets in California is processed and reused as aggregate base throughout the State. The California Department of Transportation's specification for aggregate base allows any mixture of recycled concrete aggregate and recycled asphalt pavement. This provides contractor's with the freedom to choose the base material providing the most economical base available. The City of San Francisco is developing a specification allowing RCA in all non-structural concrete applications. This permits its use in curbs, gutters and sidewalks. The California Department of Transportation is also working on a similar specification for their use.

### **2.1.7. Advantages of using RCA**

The advantage of using RCA can be summarizing in four main categories:

#### ***2.1.7.1.Angularity of RCA***

- Helps to increase structural strength in the base, resulting in improved load carrying capacity.
- Better control over gradation, RCA is able to meet gradation and angularity requirements.
- RCA shows a better performance when used in base and sub base due to the cement binds.

#### ***2.1.7.2.Resource Conservation***

- The use of recycled concrete pavement eliminates the development of waste stockpiles of concrete and reduces land disposal and dumping. Also, since recycled material can be used within the same metropolitan area, this can lead to a decrease in energy consumption from hauling and producing aggregate, and can help improve air quality through reduced transportation emissions.

### ***2.1.7.3.Economic Benefits***

- Recycled concrete is crushed and the entire aggregate product can be used as a base material according to specifications, generating no waste. This can be done on the project site or at nearby recycling plants.
- Disposal of concrete rubble and other waste construction materials by dumping or burial is a less attractive and more expensive option. Reconstruction of urban streets and expressways result in an enormous amount of waste concrete creating a massive disposal problem. Recycling can alleviate some of these problems and offer savings to the owner agencies in terms of material acquisition and disposal costs.
- Overall project savings may be considerable, using a less virgin aggregate. This saving is increased by the reduction of transportation and disposal costs.
- Other economic benefits include is the recovery of steel from the recycling process. This material usually becomes property of the contractor, who can sell as scrap metal. The potential for cost savings in many areas where aggregates are not locally available, and have to be hauled long distances (often 50 miles or more). Also environmental impact reduction and extending available life of landfills is a long-term benefit that can be experienced by local governments.

#### ***2.1.7.4.Environmental Benefits***

- Reconstruction of urban streets and expressways results in enormous waste concrete, creating a massive disposal problem. Recycling can eliminate many of these issues.
- In Minnesota, RCA is being included in a permanent rule. Beneficial Use of Solid Waste, where RCA will not be subject to review or permitting by Pollution Control Agency. The use of Solid Waste Rule will be instrumental in establishing a database of information on other non-RCA recycled source materials, conditional uses, evaluation process, and stockpiling requirements.

#### **2.1.8. Disadvantages of using RCA**

- Research has identified an increase in creep and shrinkage when using RCA in new concrete.
- RCA has a lower compressive strength than new concrete, because recycled concrete has a lower density than virgin aggregate.
- There is a high alkali content in the RCA.
- Also, there is an increase demand of water because of the high absorption of RCA.



## **2.2. Alkali-Silica Reaction (ASR)**

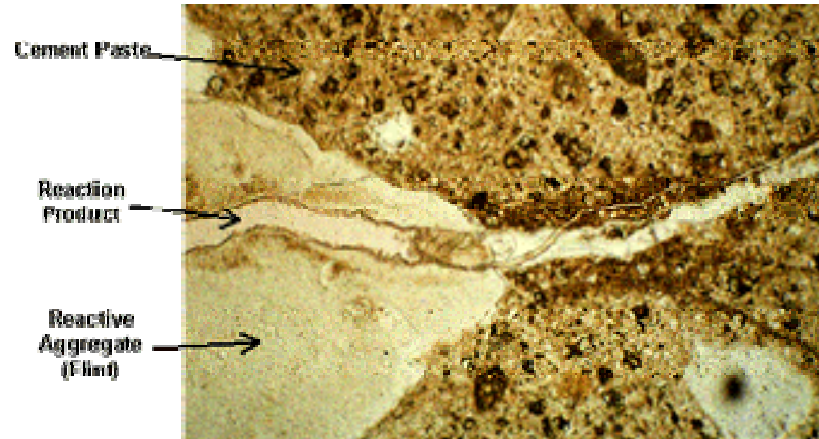
Alkali-Silica Reaction (ASR) is one type of Alkali-Aggregate Reaction (AAR). Alkali-Carbonate Reaction (ACR) is also a subset of AAR, but is far less common than ASR. ASR occurs between the alkalis produced from the hydration of Portland cement and certain siliceous rocks or minerals in the aggregates used in concrete production. The siliceous rocks or minerals include opal, chert, chalcedony, tridymite, cristobalite, and others (CSA, 2000b).

### **2.2.1. Mechanism of ASR**

Deterioration and expansion due to ASR is a two step process. First, silica in the aggregate reacts with alkalis from the hydrated cement, forming a silica gel. Second, the gel absorbs water and swells, causing enough pressure to crack the concrete.

### **2.2.2. Symptoms of ASR**

ASR in concrete begins first with the impact on the microstructure of concrete and concluding with the manifestation in concrete structures. Figure 2.8 shows a thin-section cut from concrete affected by ASR, which is viewed under transmitted-light microscopy. The reaction product of ASR gel is shown, as a crack forming through the aggregate and extending into the surrounding cement paste. The crack itself also is filled with ASR gel. This type of damage is typical of ASR-induced deterioration at the micro structural level of concrete.

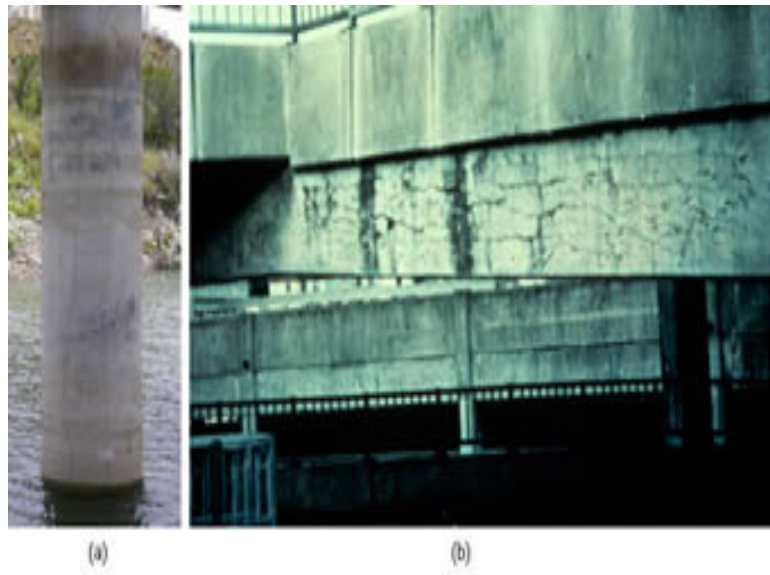


*Figure 2-8: Thin-section cut of ASR-damaged concrete, showing ASR gel and typical crack pattern through aggregate and into surrounding matrix. (FHWA, ASR)*

The outward manifestation of ASR distress in actual concrete structures varies, depending on the severity of the attack, exposure conditions, type of structure, amount and direction of restraint (internal or external), and other factors. The most important factors in determining the physical manifestation, of ASR-induced damage in field structures, are the role of restraint on subsequent crack patterns. Restraint may originate either from external sources, such as adjacent structural elements applied loads, or internal sources, such as reinforcing steel (conventional, prestressed, or posttensioned). Figure 2.9 shows typical ASR-induced damage in unrestrained concrete, resulting in classic map-cracking. Figure 2.10 shows similar damage in restrained concrete structures, where cracking tends to align itself in the direction of the main reinforcement (principal stress direction).



*Figure 2-9: ASR-induced damage in unrestrained concrete element. Uniform expansion in all directions results in classic map-cracking. (FHWA, ASR)*



*Figure 2-10: ASR-induced damage in restrained concrete elements, including (a) reinforced concrete column, and (b) prestressed concrete girder (FHWA, ASR)*

When field structures suffer from excessive expansion due to ASR, significant misalignment (with respect to adjacent elements) may occur, as shown in Figure 2.11. For pavements suffering from ASR, the subsequent expansion can lead to extrusion of joint-sealing material or even joint failure, as seen in Figure 2.12.



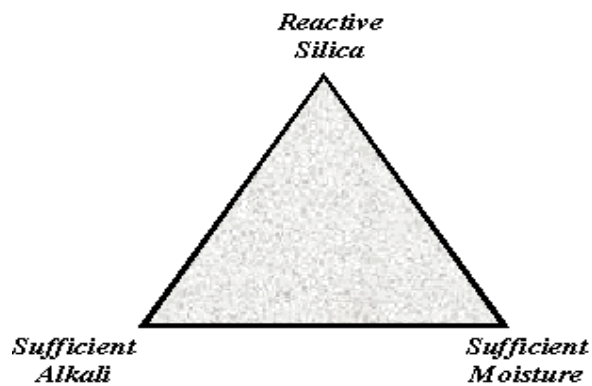
*Figure 2-11 Misalignment of adjacent sections of a parapet wall on a highway bridge due to ASR-Induced expansion (SHRP-315, 1994).*



*Figure 2-12 Extrusion of joint-sealing material triggered by excessive expansion from ASR (FHWA, ASR).*

### **2.2.3. Essential Components of ASR**

The three essential components necessary for ASR-induced damage in concrete structure (shown in Figure 2.13) are (1) reactive silica (from aggregates), (2) sufficient alkalis (mainly from Portland cement), and (3) sufficient moisture. Eliminating any one of the above components effectively will prevent damage caused by ASR.



*Figure 2-13: Three necessary components for ASR- induced damage in concrete (FHWA, ASR).*

#### **2.2.3.1. Reactive Silica**

The use of reactive aggregates in concrete is necessary for ASR to occur. The term reactive refers to aggregates that tend to breakdown under exposure to the highly alkaline pore solution in concrete. Subsequently they react with the alkali-hydroxides (sodium and potassium) to form ASR gel.

### ***2.2.3.2.Sufficient Alkalis***

The presence of sufficient alkalis is another requirement for ASR. The source of alkalis can be from any of the following items:

- Portland cements
- Supplementary cementing materials (e.g. fly ash, slag, and silica fume)
- Aggregates
- Chemical admixtures
- External sources (e.g. seawater and deicing salts)
- Wash water (if used)

Portland cement is the main contributor of alkalis. Tests have been done to evaluate the effect of alkalis in ASR. Figure 2.14 illustrates the effects of the alkali content of the concrete on expansion, using ASTM C 1293. Using an expansion limit of 0.04 %, the graph shows that laboratory concrete containing less than  $3.0 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$  was generally resistant to excess expansion, even after 2 years of testing.

Although laboratory tests have shown that keeping the total alkali content below  $3.0 \text{ kg/m}^3 \text{ Na}_2\text{O}_e$  is an effective method of limiting expansion, Figure (2.14), field structures have exhibited damage with even lower alkali loading, This especially happens when alkalis have also been contributed by the aggregates in the mixture or by external sources, such as deicing salts. Thus, when considering imposing a limit on the alkali content for a

given concrete mixture, consideration should be given to the aggregate type and reactivity, exposure conditions, and nature of the structure.

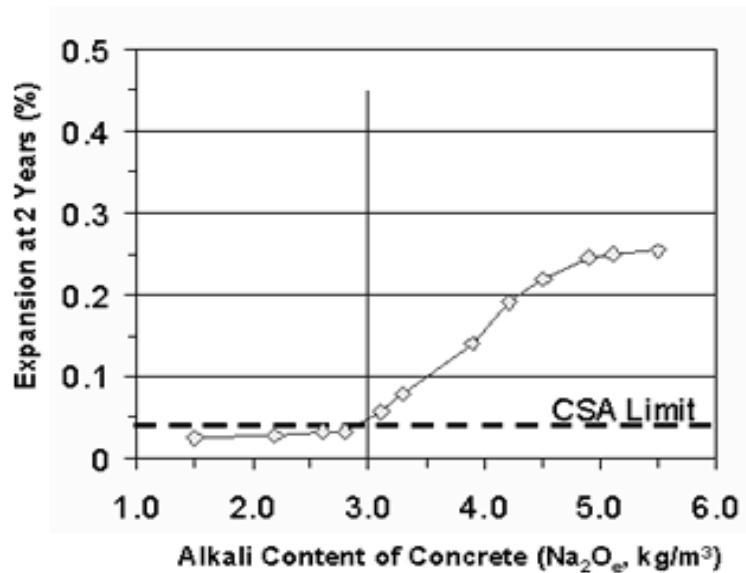


Figure 2-14: Effect of alkali content on expansion using ASTM C 1293 (Thomas, 2002).

### 2.2.3.3. Sufficient Moisture

Available moisture is important when considering the potential for ASR-induced damage in field structures. Concrete mixtures comprised of highly reactive aggregates and high-alkali cements have shown little or no expansion in certain very dry environments.

Effect of moisture on expansion are shown in Figure 2.15, where 5 different reactive aggregates were stored under different moisture conditions and the expansion of concrete prisms (ASTM C 1293) was assessed (Pedneault, 1996). In this experiment, concrete that was maintained in an environment with less than 80 % relative humidity did not undergo significant expansion (expansion was less than 0.04 % after 2 years).



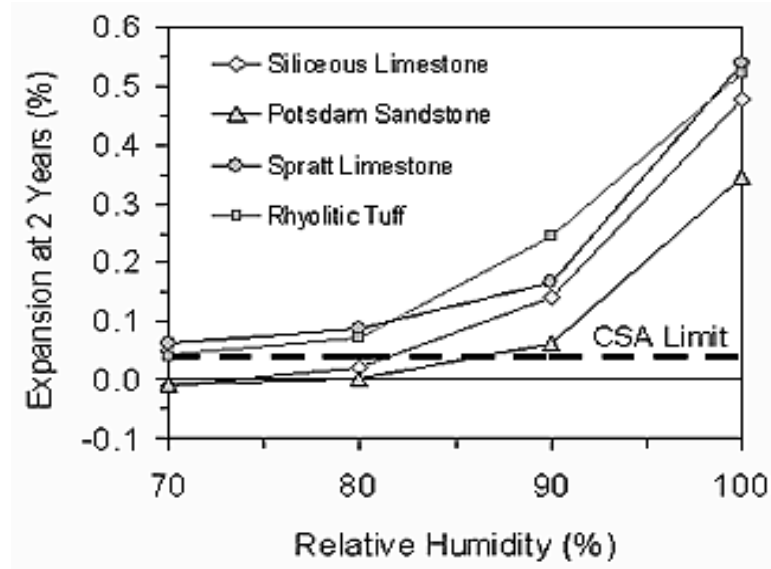


Figure 2-15: Effect of relative humidity on expansion using ASTM C 1293 (Pedneault, 1996).

#### 2.2.4. Minimizing and Preventing ASR in new Concrete

- The most common methods of minimizing the risk of expansion due to ASR include
- using non-reactive aggregates
- limiting the alkali content of concrete.
- using Supplementary Cementing Materials (SCAs).
- using lithium compounds.

#### ***2.2.4.1.Using non-Reactive Aggregates***

Using non-reactive aggregates is certainly a valuable method of preventing ASR- induced damage. However, to use this approach, we must have a very high level of confidence that the subjected aggregates are non-reactive. The aggregates must be tested using ASTM C 1260 and ASTM C 1293.

#### ***2.2.4.2.Limiting the Alkali Content of Concrete***

Limiting the alkali content of concrete mixtures below some value is generally effective in preventing ASR-induced damage, but this approach is not effective by itself. For example, aggregates that are durable at relatively low alkali contents may become more reactive when exposed to higher alkali content under field condition.

#### ***2.2.4.3.Using Supplementary Cementing Materials***

The use of SCMs to control ASR in concrete is the most common mitigation measure used in concrete construction. The benefits of properly using SCMs include not only ASR mitigation, but also improved resistance to other durability problems. This includes sulfate attack, corrosion of reinforcing steel, and freezing and thawing. The benefits related to ASR mitigation are both physical in nature (reducing permeability) and chemical (SCMs affect pore solution alkalinity, alkali binding, and other parameters).

This will minimize the risk for ASR-induced damage by the prudent use of SCMs, including fly ash, ground-granulated blast furnace slag, and silica fume.

#### ***2.2.4.4. Using Lithium to mitigate ASR Effects***

Using lithium compound, especially lithium nitrate ( $\text{LiNO}_3$ ) is a viable approach to control, and will be investigated further in this thesis.

### **2.3. Using Lithium to Mitigate ASR Effects**

Research in the early 1950s found that lithium compounds were effective in preventing the expansion related to ASR (Mc Coy and Caldwell, 1951). Interest in using lithium to preventing ASR was renewed by studies performed in the Strategic Highway Research Program (SHRP) (Stark et al., 1993). The result of recent work on lithium compounds has been promising, and the potential exists for the use of these materials in concrete as an alternative to other measures for preventing damage caused by ASR.

#### **2.3.1. Basics of Lithium**

Lithium is an alkali metal found in group A on the periodic table and has an atomic number of 3. Lithium is a soft, silver-white metal and has the lightest density of all the metals (about .53 g-centimeters). Lithium is a very active metal because of its tendency to expel its outer electron. It does not occur freely in nature, but rather it is bound in stable salts or minerals.

### **2.3.2. Laboratory research on using Lithium as an Admixture**

Many laboratory studies have focused on the use of lithium compounds to control ASR. McCoy and Caldwell (1951) were the first researchers to identify lithium compounds as effective admixtures in controlling ASR. Their study included the use of LiCl, Li<sub>2</sub>CO<sub>3</sub>, LiF, Li<sub>2</sub>SiO<sub>3</sub>, LiNO<sub>3</sub>, and Li<sub>2</sub>SO<sub>4</sub> at various dosages. Testing was performed according to ASTM C 227, with Pyrex glass as the reactive aggregate. Each of the lithium compounds were found to be effective in minimizing expansion.

Table 2.2 contains the expansion data (at various ages) for mortar bars containing different lithium compounds, where the dosages listed are based on mass of cement. A more convenient and useful method of displaying this data is to express expansion as function of the lithium-alkali molar ratio. Figure 2.16 shows the relative expansion of mortar bars containing lithium to a control without lithium (where a value of 1.0 reflects no effect on expansion) plotted against the lithium-alkali ratio. The ratio is equal to the moles of lithium divided by the moles of sodium plus potassium. As the amount of lithium in mortar increased, the relative amount of expansion decreased. The data indicated that a molar ratio of lithium to alkali of 0.74 or above was sufficient to efficiently suppress expansion.

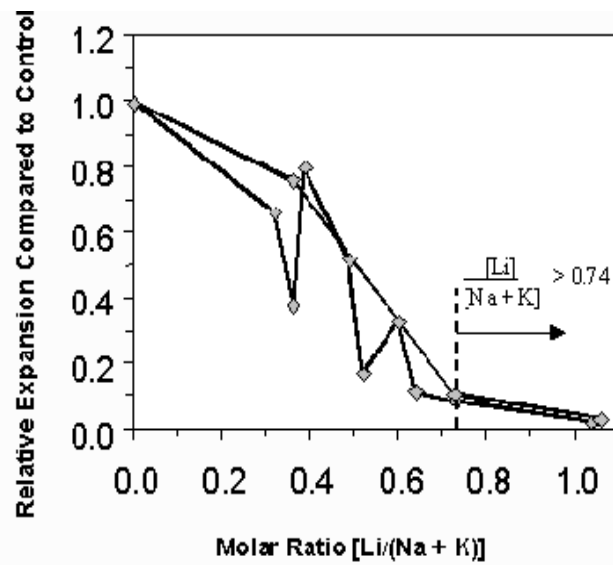


Figure 2-16: Relative expansion of mortar bars containing lithium compounds (Mc Coy and Caldwell, 1951).

*Table 2-2 Effects of lithium compounds on mortar bar expansion (McCoy and Caldwell, 1951)*

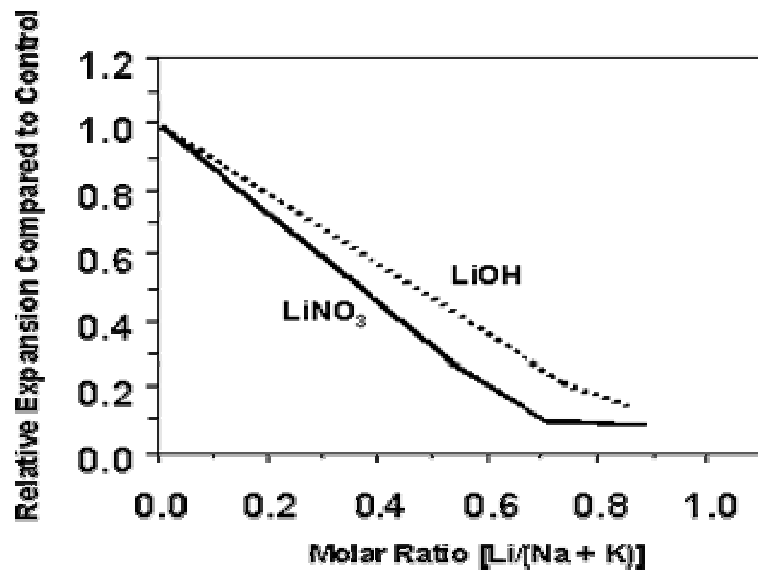
<b>Lithium Salts</b>	<b>% Addition (by mass of cement)</b>	<b>% Lesser Reduction in Expansion 100 indicate no change in expansion</b>			
		<b>2 weeks</b>	<b>4 weeks</b>	<b>6 weeks</b>	<b>8 weeks</b>
<b>Lithium Chloride</b>	0.50	75	43	34	34
<b>Lithium Chloride</b>	1.00	90	91	90	88
<b>Lithium Carbonate</b>	0.50	89	68	67	62
<b>Lithium Carbonate</b>	1.00	94	94	93	91
<b>Lithium Fluoride</b>	0.50	92	92	89	82
<b>Lithium Fluoride</b>	1.00	97	99	98	98
<b>Lithium Nitrate</b>	1.00	81	72	31	20
<b>Lithium Sulfate</b>	1.00	88	72	53	48

### ***2.3.2.1. Advantage of Lithium Nitrate***

Recent studies show that, lithium nitrate has a better ability to control ASR than any other lithium compound. Stokes et al reported that a major advantage of  $\text{LiNO}_3$  over other lithium compounds is that  $\text{LiNO}_3$  does not increase the pH of the pore solution. Using  $\text{LiNO}_3$  avoids increasing the pH because its addition to cement paste results in an increase in the lithium and nitrate ion concentrations of the pore solution with no significant increase in the OH concentration (Stokes et al., 1997). The implication of this behavior was confirmed in this study. All mortar bars containing  $\text{LiNO}_3$ , regardless of dosage, expanded less than the control (which was not the case for previous studies using other lithium compounds like  $\text{LiOH}$ ). Another important advantage of using  $\text{LiNO}_3$  as an admixture is that it is closer to a neutral pH than other lithium compounds, making it safer to handle.

A comprehensive study was initiated at the Building Research Establishment (BRE) in 1994 using lithium compounds ( $\text{LiOH}$  and  $\text{LiNO}_3$ ) to control ASR. Blackwell et al. (1997) reported on the preliminary findings and Thomas et al. (2000) gave a more recent update on the status of the project, including over 150 concrete mixtures, laboratory testing (using ASTM C 1260 and ASTM C 1293), and exposure block testing at an outdoor site located at the BRE in the United Kingdom. The program involved the use of several reactive aggregates found in the UK and also included the use of fly ash and slag. In Blackwell et al findings (Figure 2.17), a lithium to alkali molar ratio of approximately 0.70 was sufficient to control expansion when using  $\text{LiNO}_3$ , and a higher dosage, around

0.85 (molar ratio) was required for LiOH, mainly due to the impact of LiOH on pore solution pH. The study also illustrated that the ability of lithium to reduce expansion is a strong function of aggregate reactivity (i.e. more reactive aggregates require more lithium), and using fly ash in conjunction with lithium yielded synergistic reductions in expansion.



*Figure 2-17: Relative expansion of concrete prisms containing lithium compounds  
Blackwell et al. (1997)*

Diamond (1999) provided further discussion of the work previously described by Stokes et al. (1997), including additional insight into the role of LiNO<sub>3</sub> in suppressing ASR-induced expansion. He noted that LiNO<sub>3</sub> does not raise pore solution pH. Summaries of laboratory tests done on lithium component are in Table 2.3.



*Table 2-3: Summary of selected research findings relating to lithium dosages.*

Molar ratios are used, unless otherwise noted.

<b>Study</b>	<b>Test Method</b>	<b>Reactive Aggregate</b>	<b>Lithium Compound(s)</b>	<b>Minimum Molar Ratio Li:(Na + K) Needed to Suppress Expansion*</b>
McCoy and Caldwell (1951)	ASTM C 227	Pyrex glass	LiCl, Li <sub>2</sub> CO <sub>3</sub> , LiF, Li <sub>2</sub> SiO <sub>3</sub> , LiNO <sub>3</sub> , Li <sub>2</sub> SO <sub>4</sub>	0.74
Sakaguchi et al. (1989)	ASTM C 227	Pyrex glass, pyroxene and site sand	LiOH•H <sub>2</sub> O, LiNO <sub>2</sub> , Li <sub>2</sub> CO <sub>3</sub>	0.90
Stark (1992); Stark et al. (1993)	ASTM C 227 ASTM C 1260	RhyoliteGranite gneiss	LiOH•H <sub>2</sub> O, LiF, Li <sub>2</sub> CO <sub>3</sub>	0.6 (LiF)0.92 (Li <sub>2</sub> CO <sub>3</sub> )0.75-1.00 (LiOH)
Blackwell et al. (1997);Thomas	ASTM C 1293	Various United Kingdom aggregates	LiOH, LiNO <sub>3</sub>	0.70 (for LiNO <sub>3</sub> ) 0.85 (for LiOH)

### **2.3.3. Economic of using Lithium Compounds in new Concrete**

- The cost of lithium is quite high compared to other concrete materials. It is clear that adding lithium to concrete increases the cost of the raw materials and in many cases, other less-expensive alternatives are selected, such as using appropriate amounts of SCMs. However, when considering the use of lithium in new concrete, other factors must be taken into account. these factors include the following.
- If the alternative is transporting non-reactive aggregates or low-alkali cement over a long distance, or high-quality SCMs are not locally available, lithium becomes much more competitive.
- For some highly reactive aggregates, relatively high dosages of fly ash or slag may be required to control expansion. However these higher replacement levels would have a significant effect on early-strength gain and related constructability issues. Using lower dosages of fly ash or slag, in combination with lithium, can then improve the early strength properties.
- Some agencies and organizations have limited the maximum amount of SCMs mainly because of perceived concerns with salt scaling. Using lithium in these instances in combination with lower dosages of SCMs becomes a viable alternative.
- For certain concrete structures (dams or airfield pavements); very little expansion can be tolerated before the expansion impacts performance or function of the structure. Using lithium in such structures, preferably in conjunction with SCMs, is a mitigation method worthy of consideration. Those designing and constructing

these types of sensitive structures are generally more willing to spend additional money to ensure the desired function of the structure for the desired service life.

Lithium treatment of ASR-affected concrete is unlikely to be a lasting and complete solution to the problem. At best, such treatment may retard the deterioration process and delay the time until more permanent repair or replacement becomes necessary. Also, lithium treatment usually will only be considered when some level of deterioration is already present, and additional strategies may have to be considered to improve the existing condition of the concrete. However, extending the time until a more expensive repair or replacement option may still be a valuable alternative.

## **2.4. Fiber Reinforced Concrete (FRC)**

Portland cement concrete is considered to be a relatively brittle material. When subjected to tensile stresses, non reinforced concrete will crack and fail. Since mid the 1800 steel reinforcing has been used to overcome this problem, as composite system reinforced steel is assumed to carry all tensile loads. Civil structures made of steel reinforced concrete normally suffer from corrosion of the steel by salt, resulting in the failure of those structures.

Another approach is to replace the steel bars with fibers to produce a Fiber Reinforced Concrete (FRC). This method of reinforcing the concrete substantially alters the properties of the non-reinforced cement-based matrix by increasing toughness, tensile strength, and improving crack deformation characteristics.

### **2.4.1. Types of Fibers used in Concrete**

There are two main types of fiber used in concrete.

#### ***2.4.1.1. Synthetic Fibers***

Synthetic fibers are usually about 1.5" to 2" long and specially engineered for concrete. Figure 2.18 shows different types of synthetic fibers. These fibers are manufactured from man-made materials such as acrylic, nylon, polyester, polyethylene, or polypropylene.

Synthetic fibers are added to concrete before or during the mixing operation and do not require any mix design change.



*Figure 2-18: Different types of synthetic fibers*

#### ***2.4.1.2. Steel Fibers***

Steel fibers are generally 0.5" to 2.5" long and 0.017" to 0.04" in diameter. The usual amount of these fibers range from 0.25% to 2% by volume or 33 to 265 lb/cubic yard. Adding steel fiber to concrete matrix increase flexure strength reduces potential for cracking during concrete shrinkage, and increased fatigue strength.

### **2.4.2. Behavior of Synthetic Fibers in a Cement Matrix**

Behavior of synthetic can be divided into two main categories

#### ***2.4.2.1.Behavior of Synthetic Fibers in Early Age Concrete***

Early age volume changes in concrete cause weakened planes and cracks to form because of stress, which exceeds the strength of the concrete at a specific time. The growth of these micro shrinkage cracks is inhibited by mechanical blocking action of the synthetic fibers. The internal support system of the synthetic fibers prevents the formation of plastic settlement cracks. The uniform distribution of fibers throughout the concrete discourages the development of large capillaries caused by bleeding water migration to the surface. Synthetic fibers lower permeability throughout the combination of plastic crack reduction and reduced bleeding characteristics.

#### ***2.4.2.2.Behavior of Synthetic Fibers in Hardened Concrete***

Behavior of FRC under loading can be understood from Figure 2.19. The plain concrete structure cracks into two pieces when the structure is subjected to the peak tensile load and cannot withstand further load or deformation. The fiber reinforced concrete cracks at the same peak tensile load, but does not separate and can maintain a load over a large deformation. The area under the curve shows the energy absorbed by the FRC when subjected to tensile load. This can be termed as the post cracking response of the FRC.

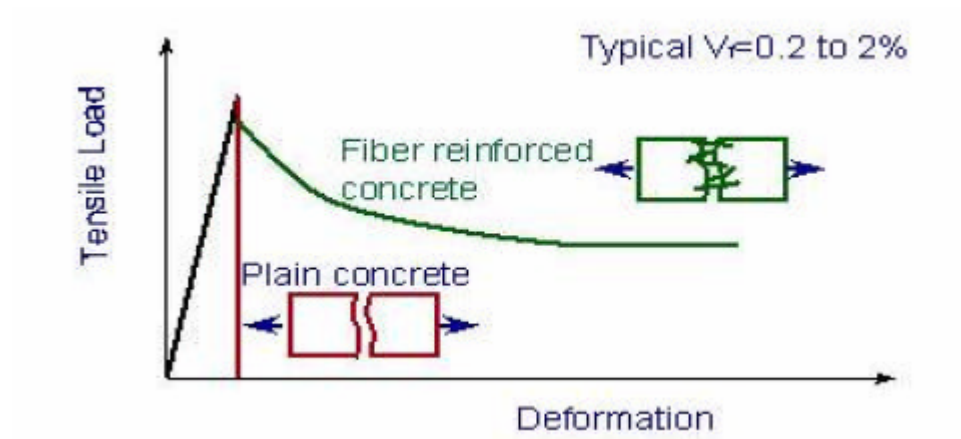


Figure 2-19: Behavior of fiber reinforced concrete under load (Brown et al, Shukla et al, and Natarajine et al 2003)

## **CHAPTER 3**

### **TEST PROGRAM**

#### **3.1. Concrete made with Recycled Concrete Aggregate**

The reuse of waste materials in building and highway construction has been growing since early 1980. The high demand of construction materials and building products makes them favorable to reuse recycled materials. Most of the states use RCA in road construction as a base and subbase. However, using RCA in new concrete applications is not popular since some issues limit using RCA in concrete pavement. These problems are listed below:

- 1) RCA absorbs more water than virgin aggregates, which lead to high porosity and lower mechanical strength
- 2) The chances of ASR cracks in concrete made with RCA are more likely happened since RCA has cement attached to it, which lead to high alkali. RCA comes from different sources. This will make it hard to predict the level of active aggregate. High water absorption of RCA increases the chances of ASR.

Using lithium nitrate has proven great effects in mitigating ASR in a new and existing concrete as indicated in chapter 2, thus lithium nitrate will be used in this experiment.

The use of fiber reinforced concrete has become a popular option in concrete construction because its influence on preventing segregation and reducing early shrinkage caused cracks. Fiber has ability to resist micro cracking, minimizing the propagation of cracks in aging concrete.



In this experiment we will combine both fibers and lithium for better quality concrete made from RCA.

### **3.2. Purpose of the Experiment**

The purpose of this study is to view the effects of using a combination of lithium nitrate (30% concentrated) with high performance polypropylene fiber on the mechanical properties of the concrete mixes with 100% recycled concrete aggregates. This concept was introduced by soaking fibers in lithium for enough time to allow fiber to be coated with lithium.

### **3.3. Test Procedures**

#### **3.3.1. Materials used**

- Recycled coarse aggregate from Anglo's recycled field as shown in Figure 3.1
- Virgin fine sand aggregate
- Lithium nitrate in liquid condition (30% concentrated)
- Cement type
- High performance polypropylene fiber from SI concrete as show in
- Figure 3.2.



*Figure 3-1: Recycled aggregates used in the experiment*



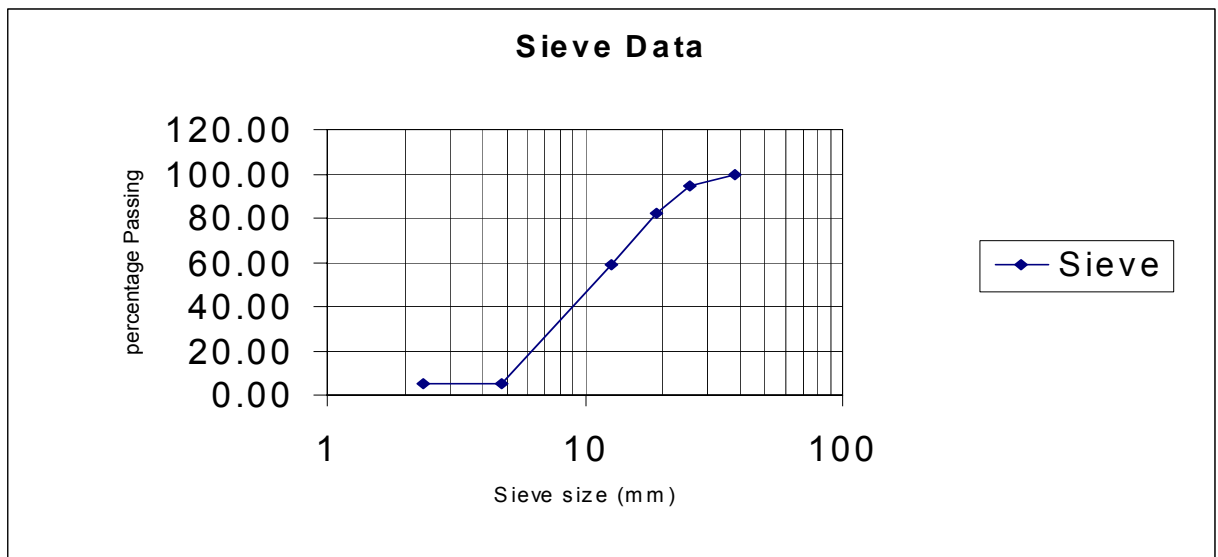
*Figure 3-2: High Performance Polypropylene Fiber used in the experiment*

## RCA Sieves Analysis

The recycled aggregates were analyzed in the lab as shown in Table 3.1 and Figure 3.3.

*Table 3-1: Sieves analysis for recycled concrete*

<b>Original Sample Weight (gm)</b>					2500
<b>US sieve weight(gram)</b>	<b>Sieve size (mm)</b>	<b>Weight retain (gm)</b>	<b>Percentage retained (%)</b>	<b>Cumulative percentage retained (%)</b>	<b>Percentage passing (%)</b>
1-1/2"	38.1	0	0.00	0.00	100.00
1"	25.4	138.3	5.53	5.53	94.47
3/4"	19.1	300.5	12.02	17.55	82.45
1/2"	12.7	588.2	23.53	41.08	58.92
no 4	4.75	1343.5	53.74	94.82	5.18
no 8	2.36	4.6	0.18	95.00	5.00
pan		118.7	4.75	99.75	0.25
		2493.8	99.75		
(D50) Median Size Particle (mm)		12	Percentage error		0.067
(D10) Effective Size Particle (mm)		5.2	USCS:well -graded gravel		
D30		7.4			
D60		8.00			
Coefficient of Uniformity:		1.54			
Coefficient of Curvature:		1.32			



*Figure 3-3: Sieves analysis for recycled concrete aggregates*

### **3.3.2. Preparation for Tests**

- Fiber was soaked in lithium for 14 days as show in Figure 3.4.
- Half of the amount of recycled coarse aggregate was saturated.
- Three boards of wood (21" × 6" × 6") were made for concrete beam samples.



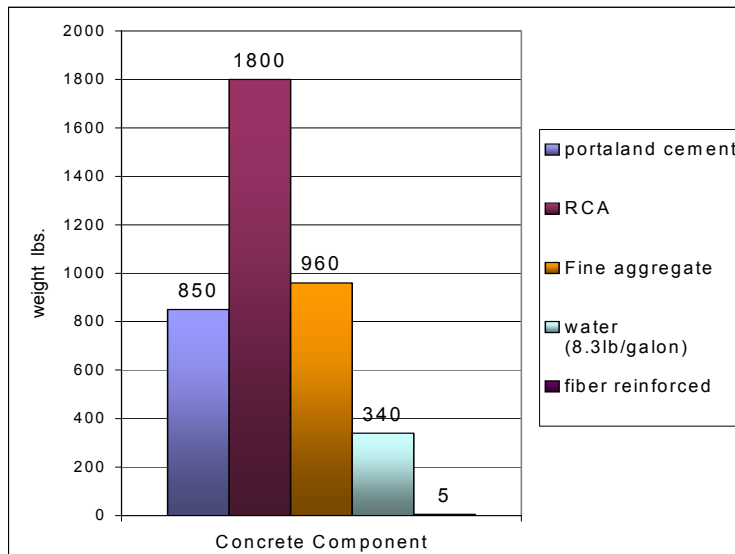
*Figure 3-4: Fiber soaked in Lithium Nitrate (30% concentration)*

### **3.3.3. Mix Design**

The mix design used in the experiment was based on weight according to (ASTM C33) and provided in Table 3.2 and Figure 3.5. The mix design did not include any air-entrained. Water to cement ratio for the mix was 0.4 and design slumps were 3-4 in. To achieve a 0.4 water-to cement ratio, the mix required 850 lb/cu yard of type 1 Portland cement. Two percent addition water was added per weight of the RCA only to the mixes with bulk RCA, this will account for the saturated surface dry conditions. The amount of fiber used was 5lb/ cu yard. An electrical barrel mixer was used to mix the samples (Figures 3.6 and 3.7). Amount of lithium attached to the fiber was 0.234 pound per one pound of fiber.

*Table 3-2: Mix design for non-air entrained concrete for medium consistency, 3-4 in slump*

Component	Weight per cubic foot (lbs)	Weight per cubic yard (lbs)	Density (lb/cu ft)
Portland cement	31.5	850	196.5
Recycled aggregate (RCA)	66.7	1800	79
Fine aggregate	35.6	960	
Water (8.3lb/gallon)	12.6	340	62.4
High Performance Polypropylene Fiber	0.2	5	
Non air-entrained		2%	
Total	146.5	3955.02	



*Figure 3-5: Amounts of concrete component used in the experiment (lb/cu yard)*



*Figure 3-6: Mixing concrete using electric barrel mixer*



*Figure 3-7: Taping the barrel sides*

### **3.3.4. Casting Concrete Samples**

#### ***Casting Cylinders***

The cylinders were grouped into two categories.

##### *1) Concrete cylinders made with bulk RCA.*

- 2 cylinders of RCA
- 2 cylinders of RCA with fiber
- 2 cylinders of RCA w/fiber soaked in lithium
- 2 cylinders of virgin concrete aggregate

##### *2) Concrete cylinders made with saturated RCA.*

- 2 cylinders of RCA
- 2 cylinders of RCA with fiber
- 2 cylinders of RCA w/fiber soaked in lithium

The cylinders were cast into three layers, each layer were rodded 25 times with a  $\frac{3}{8}$ " rod (ASHTO T23).

#### ***Casting Beams***

4 beams (21"  $\times$  6"  $\times$  6") were casted as seen in Figure 3.8.

- 1 beam with plain RCA
- 1 beam with RCA with fiber
- 1 beam with RCA w/fiber soaked in lithium
- 1 beam with virgin concrete aggregate

The beams were casted in layer according to specification (AASHTO T23).





*Figure 3-8: Casting concrete beam*

### **3.3.5. Post Casting**

After casting, lithium nitrate was added on the top of concrete samples made of RCA w/ fiber soaked in lithium.

### **3.3.6. Curing Procedure**

Samples were covered with wet towels and left to cure for 14 days (no curing room available).

### **3.3.7. Testing Samples**

Two tests were performed on the samples.

#### ***3.3.7.1. Compressive Strength Test***

This test was done on two categories of samples:

- 1) Concrete made with bulk RCA
- 2) Concrete made with saturated RCA.

Compressive strength of the mixture was determined using 4" × 8" specimens in according with ASTM C39. The compressive strength was tested at UCF structure lab using neoprene pads in steel retaining rings as show in Figure 3.9.



*Figure 3-9: Compressive test performed on concrete cylinders.*

### ***3.3.7.2.Flexure Strength Test***

Beams were tested using standard testing methods for flexural strength of concrete (using simple beam with third–point loading ASTM C78) as shown in Figures 3.10 and 3.11. All of the beams were broke at the middle span. A formula used in calculating the flexure strength is given as follows.

$$R = \frac{PL}{bd^2}$$

Where,

R= modules of rupture, (flexure strength).

P = maximum applied load indicated by the testing machine (lbf).

L= span length (in)

b = average width of beam (in)

d = average depth of specimen (in).

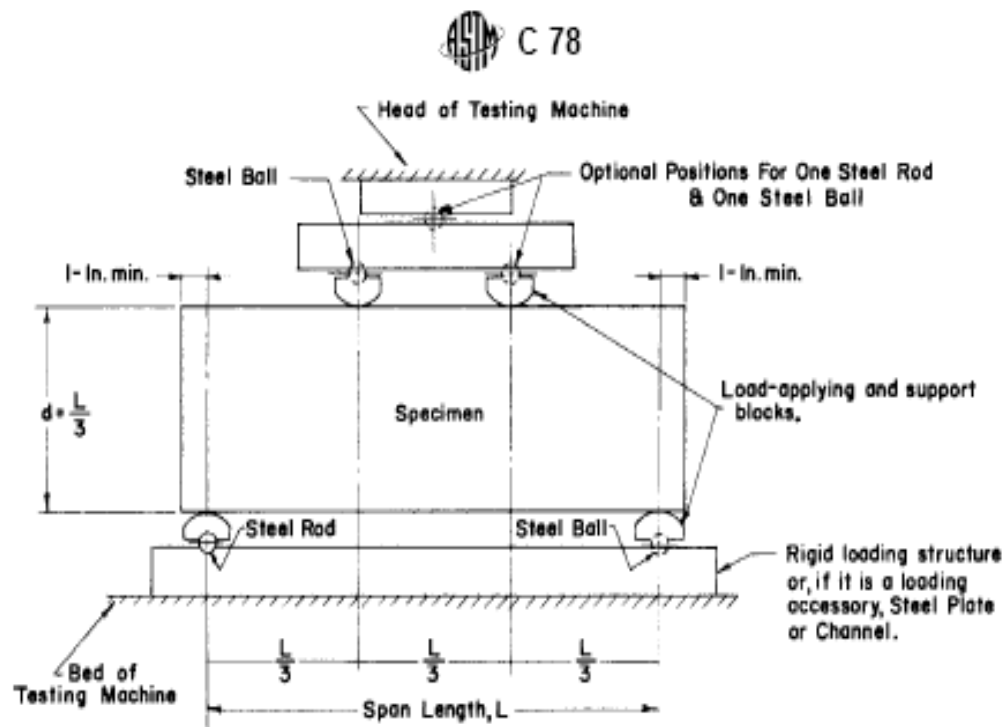


Figure 3-10: Standard test ASTM C 78



Figure 3-11: Flexure strength test

## CHAPTER 4

### RESULTS

#### **4.1. Test Results and Analysis for Concrete Cylinders made with Bulk RCA**

Compressive strength was measured and shown in 3.3 and Figures 3.12 and 3.13. As expected, the compressive strength of all concrete samples made with RCA was lower than concrete samples made with virgin aggregate. Concrete samples made of RCA with fiber and RCA w/fiber soaked in lithium have higher deformation and residual load strength. In addition, the fiber additive into RCA concrete mix reduced shrinkage cracking and prevented shatter cracks of cylinders as shown in Figures 3.14, 3.15, and 3.16. When comparing compressive strength between concrete samples made with RCA and the samples made of RCA with fiber, there is no significant difference (3680 PSI for RCA and 3623 PSI for RCA with fiber). Concrete samples made with RCA w/fiber soaked in lithium gives a higher compressive strength (3820 PSI), this might have been due to lithium nitrate additive, which mitigates the ASR effects that minimize the micro cracks and affect the mechanical properties of concrete.

*Table 4-1: Compressive strength results for concrete cylinders made with bulk RCA*

Type	Cylinder	Compressive strength 14 days, (PSI)	Average compressive strength, (PSI)
Plain RCA	cylinder1	3737 (25.77 MPa)	3680 (25.37 MPa)
	cylinder2	3622 (24.97 MPa)	
RCA with Fiber	cylinder1	3526 (24.31 MPa)	3623 (24.98 MPa)
	cylinder2	3719 (25.64 MPa)	
RCA w/fiber Soaked in Lithium	cylinder1	3805 (26.23 MPa)	3820 (26.33 MPa)
	cylinder2	3834 (26.43 MPa)	
Virgin Aggregate	cylinder1	4392 (30.28 MPa)	4434 (30.57 MPa)
	cylinder2	4475 (30.85 MPa)	

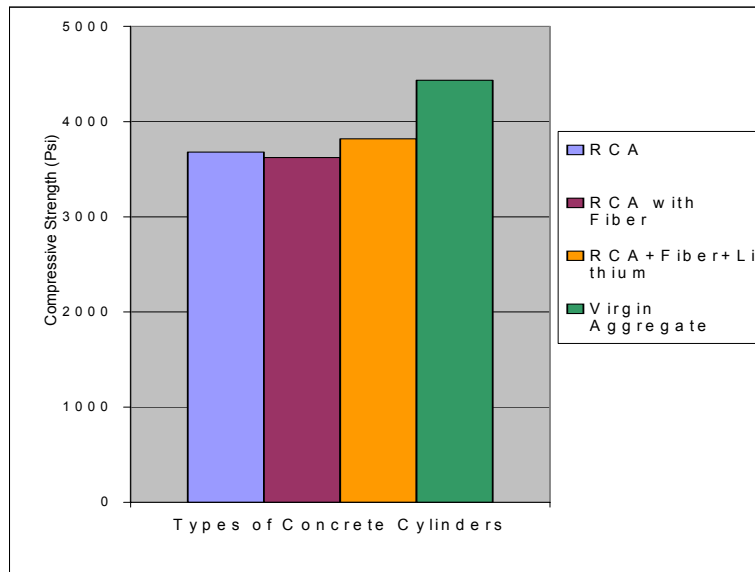


Figure 4-1: Compressive strength comparison for concrete cylinders made of bulk RCA

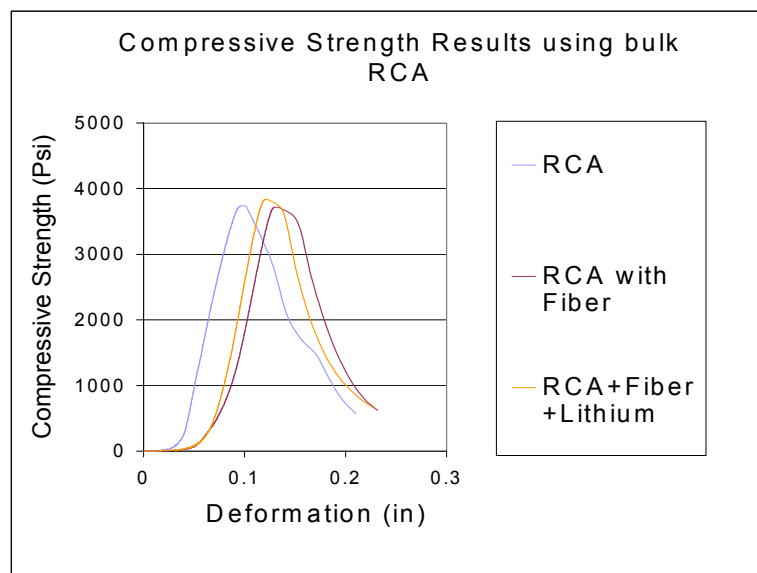


Figure 4-2: Compressive strength results for concrete cylinders made of bulk RCA

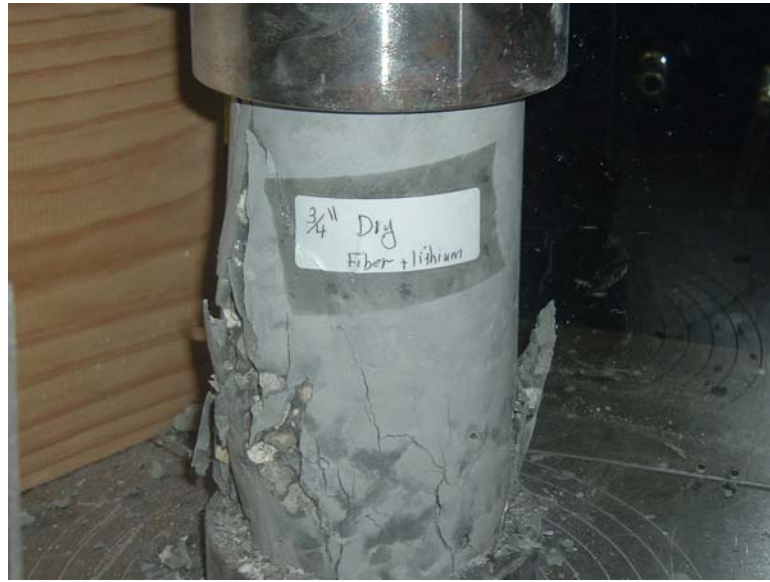


*Figure 4-3: Tested concrete cylinder made of plain bulk RCA*



*Figure 4-4: Tested concrete cylinder made of bulk RCA with fiber*





*Figure 4-5: Tested concrete cylinder made of bulk RCA w/fiber soaked in lithium*

#### **4.2. Test Results and Analysis for Concrete Cylinders mad with Saturated RCA**

As seen in Figures 3.17 and 3.18 and Table 3.4, there is a slight difference in compressive strength between concrete samples made of plain RCA and the samples made of RCA with fiber (average of 4049 for RCA, 4127 for RCA with fiber).

Concrete samples made of RCA w/fiber soaked in lithium have a higher compressive strength (average of 4309). This increase due to the effect of lithium nitrate in reducing micro cracks caused by ASR. Again, the fiber additive to concrete samples increased the residual load strength and prevented the segregation of concrete (Figures 3.20, and 3.21). All samples made of RCA have a compressive strength greater than 4000 (the minimum value required by most state department of transportation).

*Table 4-2: Compressive strength results for concrete cylinders made with saturated RCA*

Type	cylinder	compressive strength 14 days (PSI)	Average compressive strength (PSI)
Plain RCA	cylinder1	4006 (27.62 MPa)	4049 (27.92 MPa)
	cylinder2	4092 (28.21 MPa)	
RCA with Fiber	cylinder1	4152 (28.63 MPa)	4127 (28.46 MPa)
	cylinder2	4103 (28.29 MPa)	
RCA w/fiber Soaked in Lithium	cylinder1	4340 (29.92 MPa)	4309 (29.71MPa)
	cylinder2	4278 (29.50 MPa)	

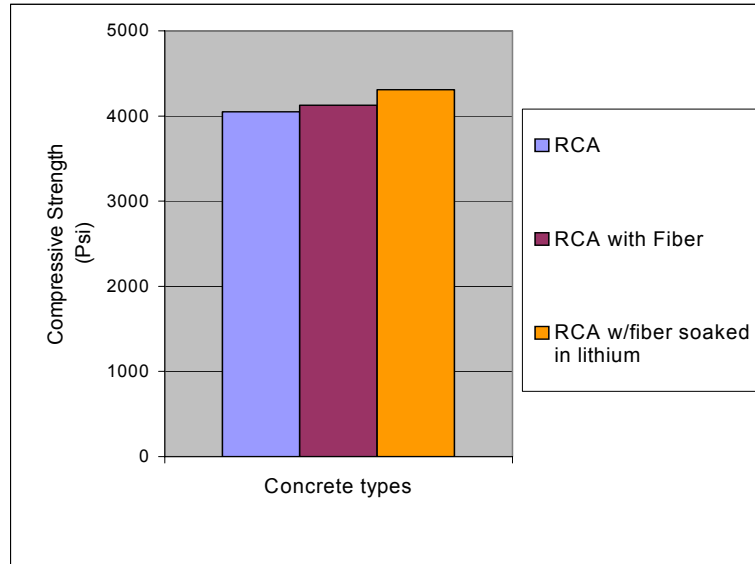


Figure 4-6: Compressive strength comparison for concrete cylinders made of saturated RCA

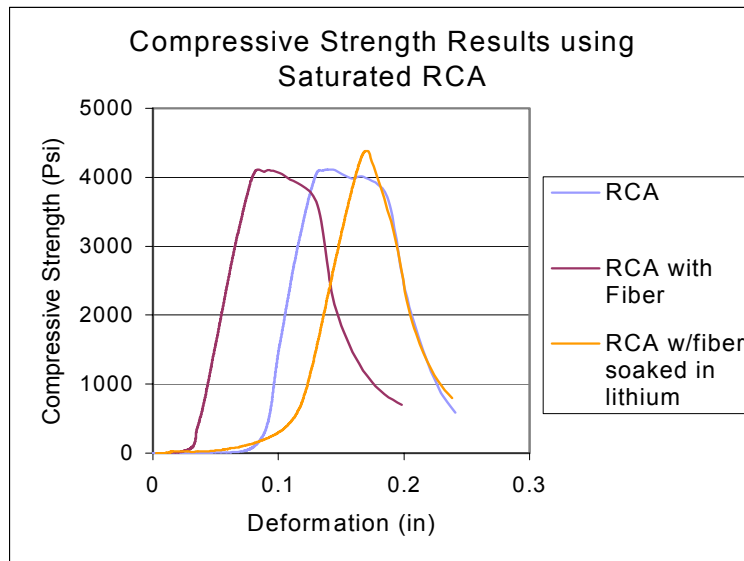


Figure 4-7: Compressive strength result for concrete cylinders made of saturated RCA



*Figure 4-8: Tested Concrete sample made of saturated RCA*



*Figure 4-9: Tested concrete samples made of RCA w/fiber soaked in lithium*



*Figure 4-10: Tested concrete sample made with saturated RCA with fiber*

#### **4.3. Comparison of Compressive Strength for Samples made with Bulk and Saturated RCA**

Compressive strength results from Tables 3.3 and 3.4 are summarized in Table 3.5 for comparison between concrete samples made with bulk RCA and concrete samples made with saturated RCA.

As seen in Table 3.5, there was an increase in compressive strength in all concrete samples made with saturated RCA. Compressive strength concrete made with saturated RCA is approximately 10% higher than the samples made with bulk RCA. The compressive strength for samples made of RCA with fiber and samples made of RCA w/fiber soaked in lithium have even higher compressive strength. The percentage increases are 14% and 12.8% respectively. Figures 3.22, 3.23, and 3.24 shows the difference of test curves in compressive strength between concrete made with bulk and those made with saturated RCA. The saturated compressive strength of RCA is consistently higher than bulk RCA concrete.

*Table 4-3: Compressive strength comparison between concrete made with bulk and saturated RCA.*

Concrete types	Compressive strength (PSI)		Compressive strength difference (PSI)	Percentage increase %
	Bulk RCA	Saturated RCA		
RCA	3680 (25.37 MPa)	4049 (27.92 MPa)	369 (2.54 MPa)	10.0%
RCA with Fiber	3622 (24.98 MPa)	4128 (28.46 MPa)	506 (3.49 MPa)	14.0%
RCA w/fiber Soaked in Lithium	3820 (26.33 MPa)	4309 (29.71 MPa)	489 (3.37 MPa)	12.8%

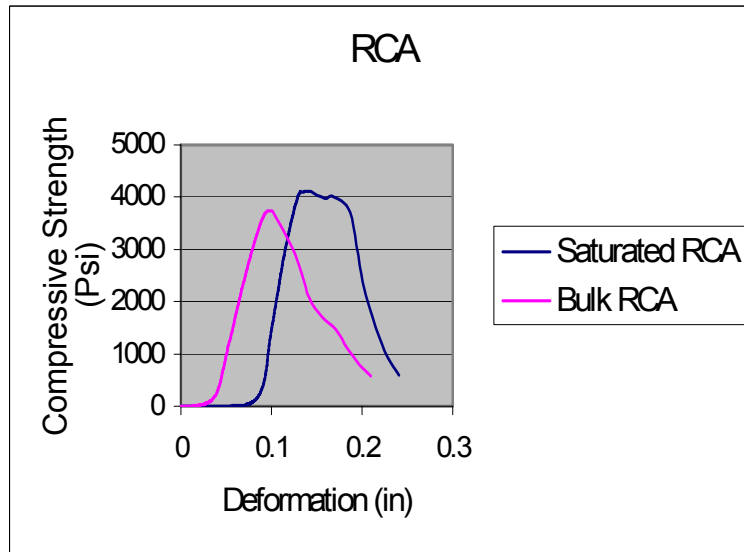


Figure 4-11: Comparison between concrete made with saturated and bulk RCA

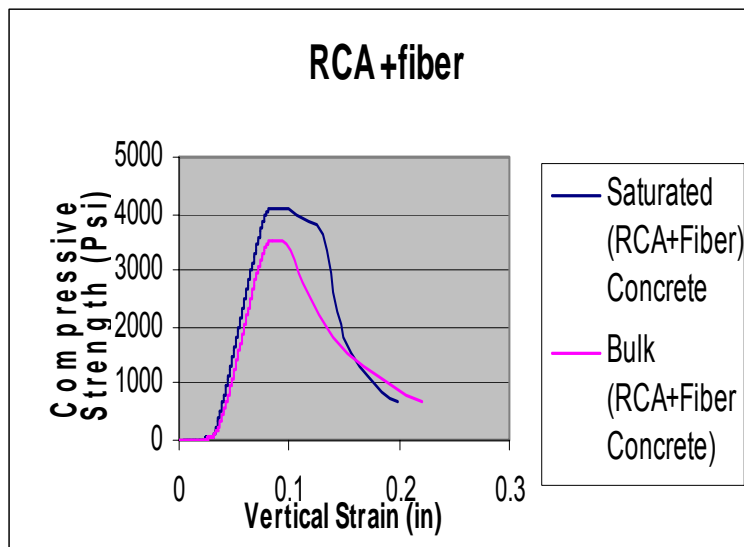
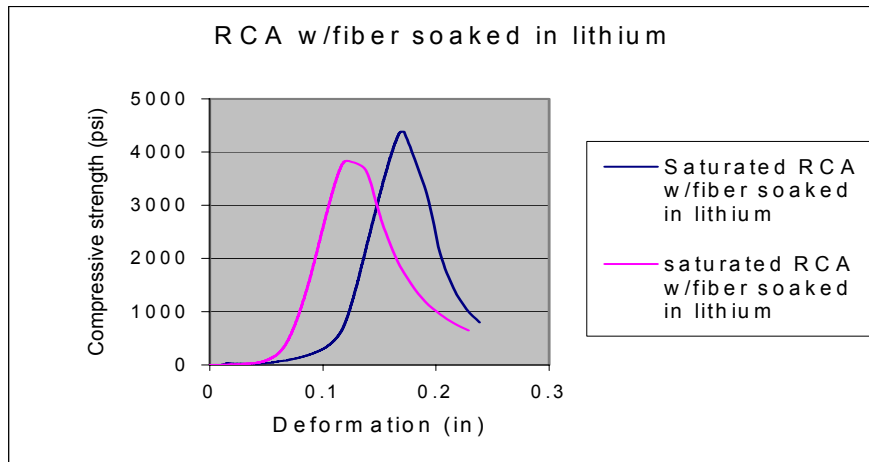


Figure 4-12: Comparison between concrete made with saturated and bulk RCA with fiber





*Figure 4-13: Comparison between concrete made with saturated and bulk RCA w/fiber soaked in lithium*

#### **4.4. Tests Results and Analysis for Beams Sample**

Similar to the phenomena of cylindrical specimens, the flexural test from beam samples perform as shown in figures 3.25 and 3.26 and Table 3.6.

On figure 3.27, the beam specimens with fiber cracks, but the beam specimen made with plain RCA (figure 3.26) was totally breaks in half. The phenomena simply indicate that the fiber provides the residual strength as stated previously.

The concrete beam made with virgin aggregate has a flexures strength value of 656 (4.52 MPa), which is higher than all beams made with RCA. Beam specimen made with RCA w/fiber soaked in lithium gives a higher flexure strength value of 637PSI (4.39 MPa)

comparing to beams made with plain RCA and RCA with fiber (574 PSI (3.96 MPa) and 621 PSI (4.19 MPa)) respectively.

*Table 4-4: Results of flexure test on beams sample.*

Type	Flexure Strength (PSI)	Percent less than virgin aggregate %
Plain RCA	574 (3.96 MPa)	12.5
RCA with fiber	608 (4.19 MPa)	7.3
RCA w/ fiber soaked in lithium	637 (4.39 MPa)	2.9
Virgin aggregate	656 (4.52 MPa)	0.0

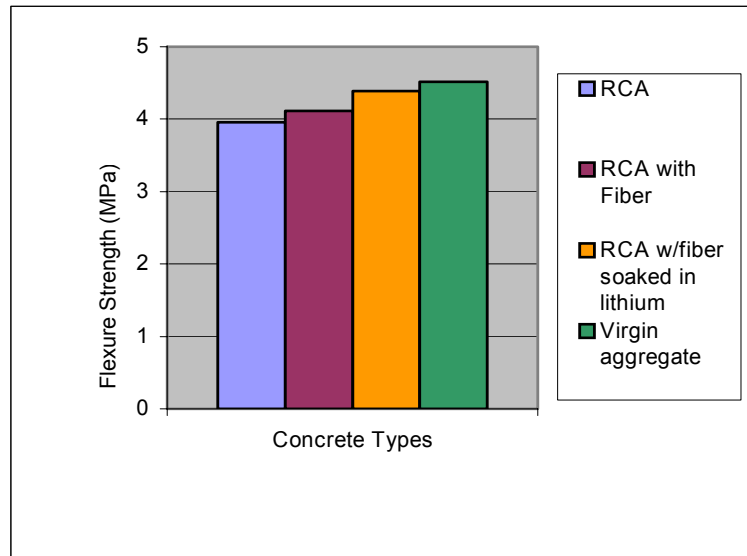


Figure 4-14: Flexure strength comparison for different beams

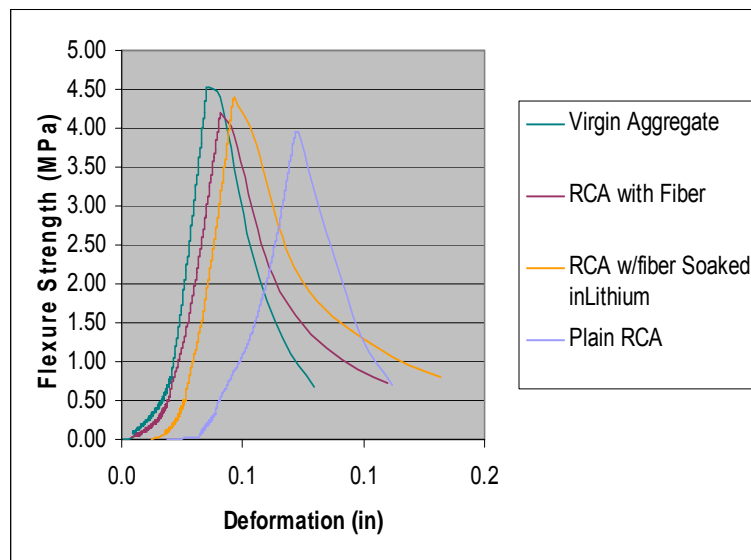


Figure 4-15: Flexure strength for different beams



*Figure 4-16: Tested concrete beam made of RCA with fiber (shows a crack but not complete separation, fiber held the two pieces together).*



*Figure 4-17: Tested beam made with RCA and no fiber (sudden break without any previous cracks).*

## **CHAPTER 5**

### **CONCLUSION AND SUMMARY**

From compressive test results of specimens made with bulk RCA, it was found that concrete cylinders made of RCA w/fiber soaked in lithium have a high compressive strength value of average 3820 PSI. On the other side, there was no significant difference in compressive strength between concrete beams made with plain RCA (3680 PSI) and RCA with fiber (3622 PSI). This increase in compressive strength for samples made from RCA w/fiber soaked in lithium indicates that the lithium additive was able to limit ASR effects, which weaken the compressive strength.

Compressive strength results for cylinders made with saturated RCA have the same phenomena as cylinders made with bulk RCA. Cylinders made of RCA w/fiber soaked in lithium have average compressive strength value of 4309 PSI average. Concrete cylinders made with plain RCA and RCA with fiber have compressive strength values of 4049 PSI and 4128 PSI respectively.

It was observed, all concrete cylinders containing fibers have a higher deflection, post crack load bearing, and no segregation of concrete. On the other side, cylinders made with plain RCA have a shattered crush and no residual load bearing.

It was interesting to compare compressive strength test results between cylinders made with bulk RCA and saturated RCA. It was found that all specimens made with saturated RCA have a higher compressive strength than specimens made with bulk RCA. This increase in compressive which ranges between 10% and 14% indicates that, using RCA at saturated surface dry condition on new concrete is essential to have a high quality concrete.

## **APPENDIX: COMPRESSIVE AND FLEXURE STRENGTH TEST RESULTS**

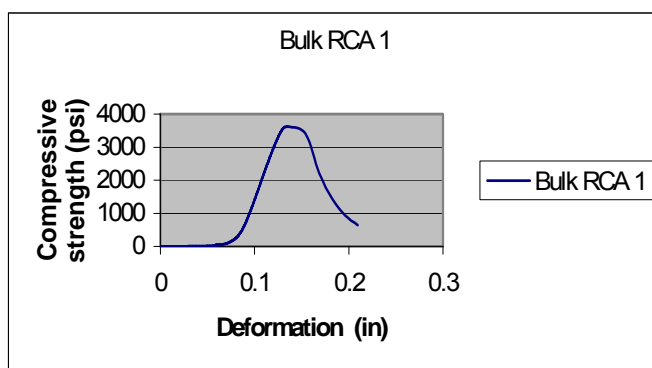


Figure A.1. Compressive strength for concrete cylinders made of bulk RCA

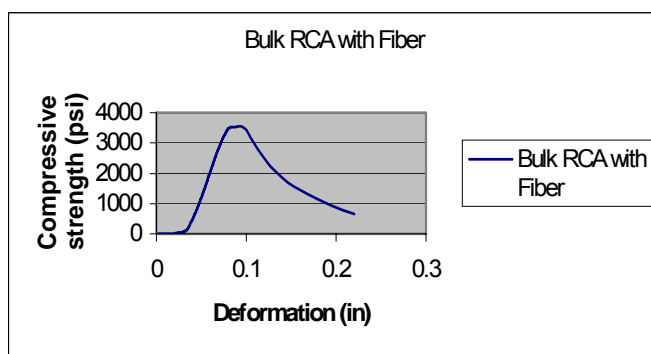


Figure A.2. Compressive strength for concrete cylinders made of bulk RCA with fiber

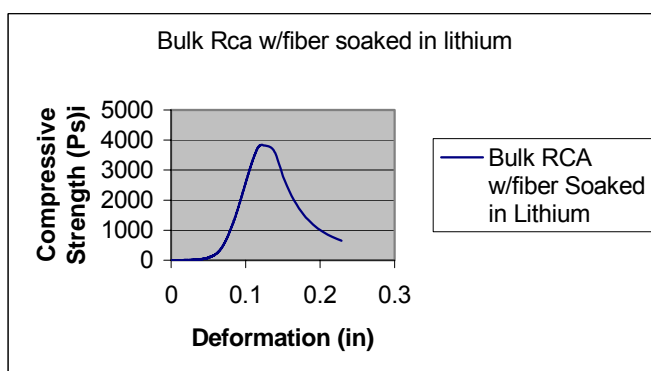


Figure A.3. Compressive strength for concrete cylinders made of bulk RCA w/fiber soaked in lithium.



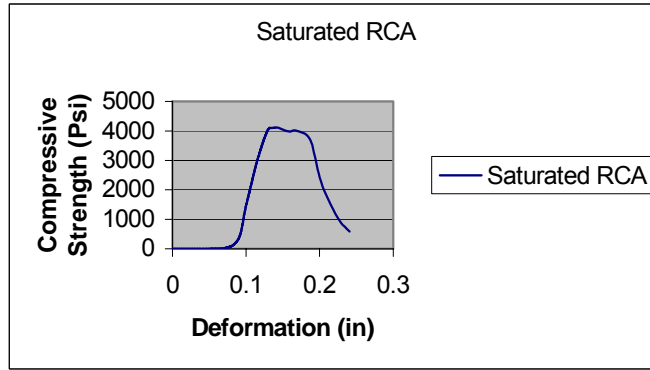


Figure A.4. Compressive strength for concrete samples made of saturated RCA.

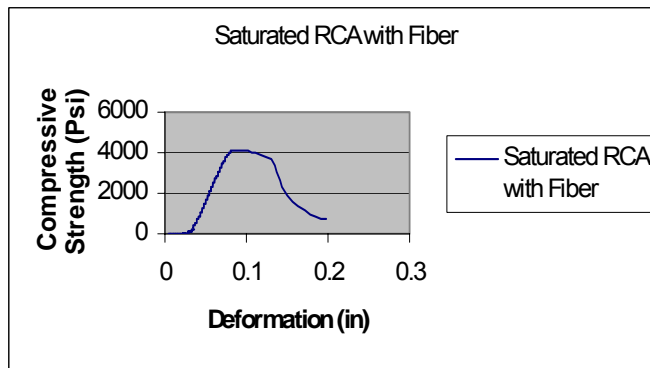


Figure A.5. Compressive strength for concrete samples made of saturated RCA with fiber

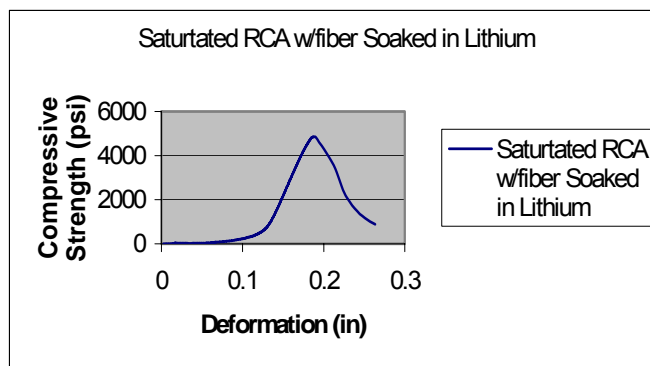


Figure A.6. Compressive strength for concrete samples made of saturated RCA w/fiber soaked in lithium

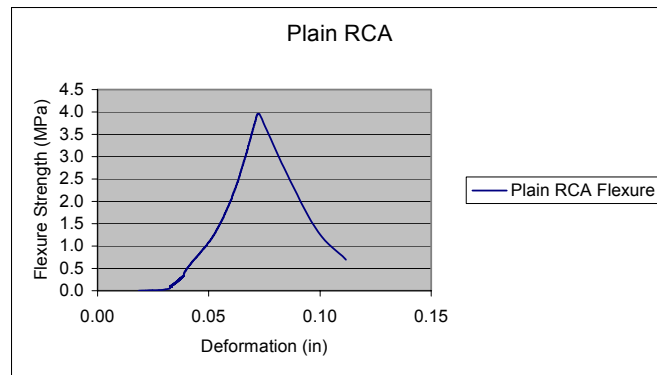


Figure A.7. Flexure strength for concrete beam made with plain RCA

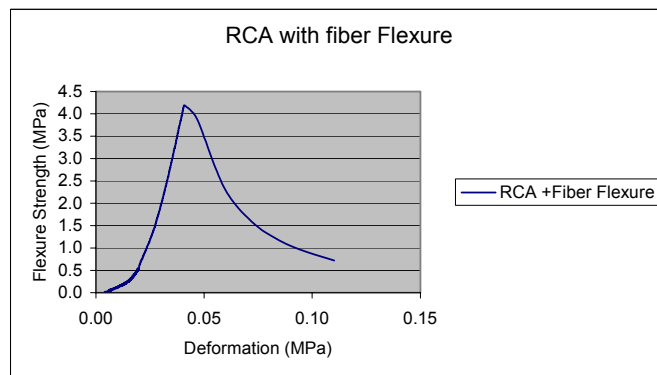


Figure A.8. Flexure strength for concrete beam made with RCA with fiber.

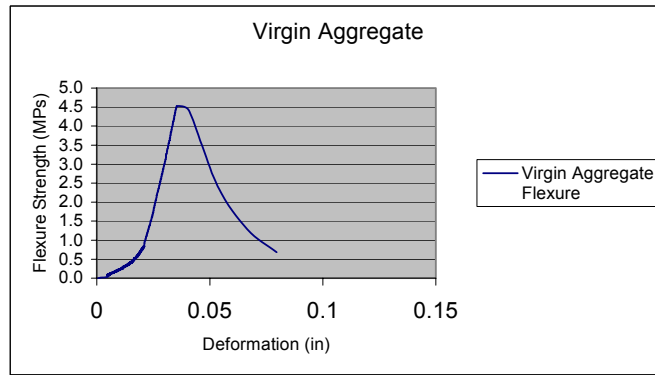


Figure A.9. Flexure strength for concrete beam made with RCA w/fiber soaked in *lithium*

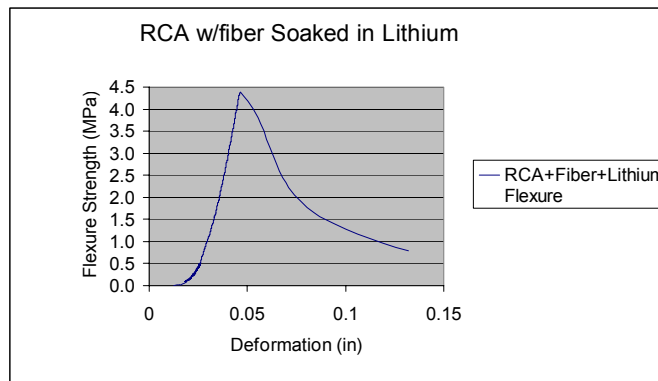


Figure A.10. Flexure strength for concrete beam made with virgin aggregate.

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